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Influence of steel properties on the ductility of doweled timber connections

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HIGHLIGHTS

- Yielding of serially arranged ductile connections does not occur systematically.
- Steel commonly used in timber connections shows unfavourable characteristics.
- Using steel with favourable post-elastic characteristics enables serial yielding.
- Steel with favourable post-elastic characteristics also increases the resistance.
- Optimized steel quality could lead to a reassessment of some design principles.

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ABSTRACT

In the seismic design of structures according to the dissipative structural behaviour, the connection ductility is crucial in order to ensure the desired level of energy dissipation of the overall structure. Therefore, in case of ductile zones composed of dowel-type fasteners arranged in series, it is important to ensure that all the fasteners can fully develop their energy dissipation capacity by plastic deformations. However, when different types of connections made of two symmetrical and serially arranged assemblies of dowel-type fasteners are tested, it often appears that only few fasteners fully work in the plastic region while most of the remaining ones exhibit very low yielding.

Looking at the causes of this dysfunction, a possible explanation is due to the fact that the rules for the seismic design of dissipative zones in timber structures given in international codes and used in common practice often make reference only to the steel quality of the dowel-type fasteners specifying a minimum tensile strength or sometime, like is the case of the current version of Eurocode 8, only to maximum values of the dowel-type fastener diameter and of the thickness of the connected timber or wood-based members. Also, the research conducted so far about the ductile behaviour of serially arranged connections was not focused on the post-elastic properties of steel. However, for the seismic design of ductile zones of other materials, such as for example is the case of reinforced concrete walls, post-elastic characteristics of steel are required for the reinforcing bars, in order to achieve the desired dissipative behaviour.

Inspired by this fact, timber connections composed of serially arranged dowels made of steel grades with different hardening ratio and elongation at maximum tensile stress were fabricated and tested. The purpose of this work is to understand if the use of steel with significant post-elastic properties may help to solve the problem of limited yielding in serially arranged dowel-type connections.

The tested specimens were composed of two symmetrical timber members made of Glulam and LVL connected to two 6 mm thick slotted-in steel plates by means of 9 steel dowels with a diameter of 6.0 mm, which were subjected to monotonic and cyclic tests carried out by implementing dowels made of steel with favourable post-elastic properties.

The results showed that the simultaneous yielding of two serially arranged dowelled assemblies is possible, although not fully. Moreover, assuming as reference the steel grade with the lowest post-elastic properties, the connection ductility and strength measured through monotonic and cyclic tests increased

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by about 30% for the steel grades with the highest hardening ratio and elongation at maximum tensile stress, whereas the displacement at maximum strength was about five times higher.

In addition, it was found that confinement of the timber members and shaping of holes were crucial in order to avoid undesired and premature brittle failures and to increase the connection strength and ductility.

The results obtained may be useful in order to bring a reassessment of the code requirements regarding the steel properties of ductile connections as well as of certain principles of dimensioning and detailing.

1. Introduction

According to Eurocode 8 [1], the seismic design of buildings can be performed according to one of the two following concepts:

- low-dissipative structural behaviour or
- medium or high-dissipative structural behaviour.

The concept of dissipative structural behaviour is based on the principle that the performance of the structure against an earthquake corresponds to the structural resistance multiplied by the ductility. In this case, a part of the energy triggered by the earthquake is dissipated by the ductile zones of the structure. Since timber shows a brittle behaviour, only mechanical joints can provide the required ductility. To ensure this ductility, the principle of the capacity design method must be applied, which according to the definition given in Eurocode 8 [1] "*… is the design method in which some elements of the structural system are chosen and suitably designed and detailed for energy dissipation under severe deformations while all other structural elements are provided with sufficient strength so that the chosen means of energy dissipation can be maintained*". Therefore, for the case of timber structures mechanical joints are chosen and suitably designed and detailed for energy dissipation under severe deformations while all other structural elements are protected against brittle failure and are purposely designed considering the overstrength of the chosen ductile zones. The ratio between the connection ductility and the structure ductility is therefore crucial. Together with the connection ductility, this ratio contributes decisively to the value of the behaviour factor.

In the case of a serial arrangement of ductile connections made of dowel-type fasteners, it is important to ensure that possibly all the assemblies can develop simultaneously their energy dissipation capacity by plastic deformation. However, when different types of timber connections made of two symmetrical and serially arranged assemblies of dowel-type fasteners are tested, it often happens that only one assembly works in the plastic region while all other assembly yields very little. Fig. 1 shows this effect of non-serial yielding of two symmetrical doweled assemblies.

Looking in detail at the picture in Fig. 1, two different phenomena can be observed: non-uniform yielding within one connection (i.e. left side in Fig. 1), non-uniform yielding between a series of connections (i.e. right side hardly yielding in Fig. 1). The initial lack of yielding within one connection in case of rows composed of several fasteners may be due to the non-uniform force distribution in the connection, i.e. fasteners located furthest from the edge exhibit higher loading and start yielding prior to other fasteners. Only after further loading in the plastic region fasteners have the ability to fully plasticise.

The non-serial yielding of all the zones designed to be ductile is a limiting aspect in the search for high structure ductility. Furthermore, frequently the ductility of timber connection derived through cyclic testing is rather small, especially when the diameter of the dowel-type fasteners exceeds that of staples or thin nails [2,3]. The observed type of failure is very common, considering that current Eurocode 5 [4] spacing requirements are inadequate to allow for fully ductile behaviour as stated in [5], and non-ductile failure generally occurs prior to full yielding especially for stocky fasteners due to mode cross-over, as observed in [6] and [7]. This is especially evident if the ductile capacity is compared with a brittle strength prediction such as in [8]. These aspects are even more important in the seismic design of buildings made of two different lateral load resisting systems made of the same or different materials which are working at the same level [9].

Looking at the causes of this dysfunction, another possible explanation is that the rules for the seismic design of dissipative zones in timber structures given in international codes and used in common practice often make reference only a minimum value tensile f_u of the steel of dowel-type fasteners or sometimes, as for example in Eurocode 8 [1], to prescriptive rules related to a maximum size of the dowel diameter or of the thickness of the connecter timber or wood-based members. However, for the seismic design of ductile zones of other materials, such as for example is the case of reinforced concrete walls, post-elastic characteristics of steel are required for the reinforcing bars, in order to achieve the desired dissipative behaviour [10].

2. Background research and code requirements

A great number of test results about the evaluation of strength, stiffness, ductility and even overstrength properties of timber-to-timber or steel-to-timber joints made with dowel-type fasteners are available in literature. Therefore, even limiting the search only to tests conducted on doweled or bolted connections, it is almost impossible to make a detailed and comprehensive literature review and compare the results of these tests with the outcomes of the present research, also considering the different test setup, joint geometry, wood species and type of wood-based product, type of dowel-type fasteners and size of the fastener diameter used in the tests, and the different topic investigated (e.g. strength, stiffness, ductility of joints, embedment properties of wood, etc.). The influence of the number of bolts in a row, the number of rows, the spacing, the loaded and distances and bolt slenderness in multiple double-shear bolted connections loaded parallel to the grain and made mostly with grade 4.6 M12 bolts have been investigated in [11]. The moment–angle relation of timber-to-timber connections with multiple dowels was investigated in [12] and a modified equation was derived in order to better evaluate the effective bending capacity of tested dowel-type fasteners. Twelve different group of specimens of wood-steel-wood bolted glulam connections were tested in [13], in order to derive design equations to better predict the load-carrying capacity of steel-to-timber dowel-type connections. Further research was conducted at TU Delft to investigate the applicability of high steel strength dowels in double shear timber-to-timber joints with one dowel [14] and double shear timber joints with slotted-in steel plates [15,16], with different combinations of wood species and steel grades. The latter tests were carried out with spruce and 8 mm vhss (very high strength steel) dowels of grade 12.9 with one, three and five dowels in a row. The main outcome of these tests was that the failure

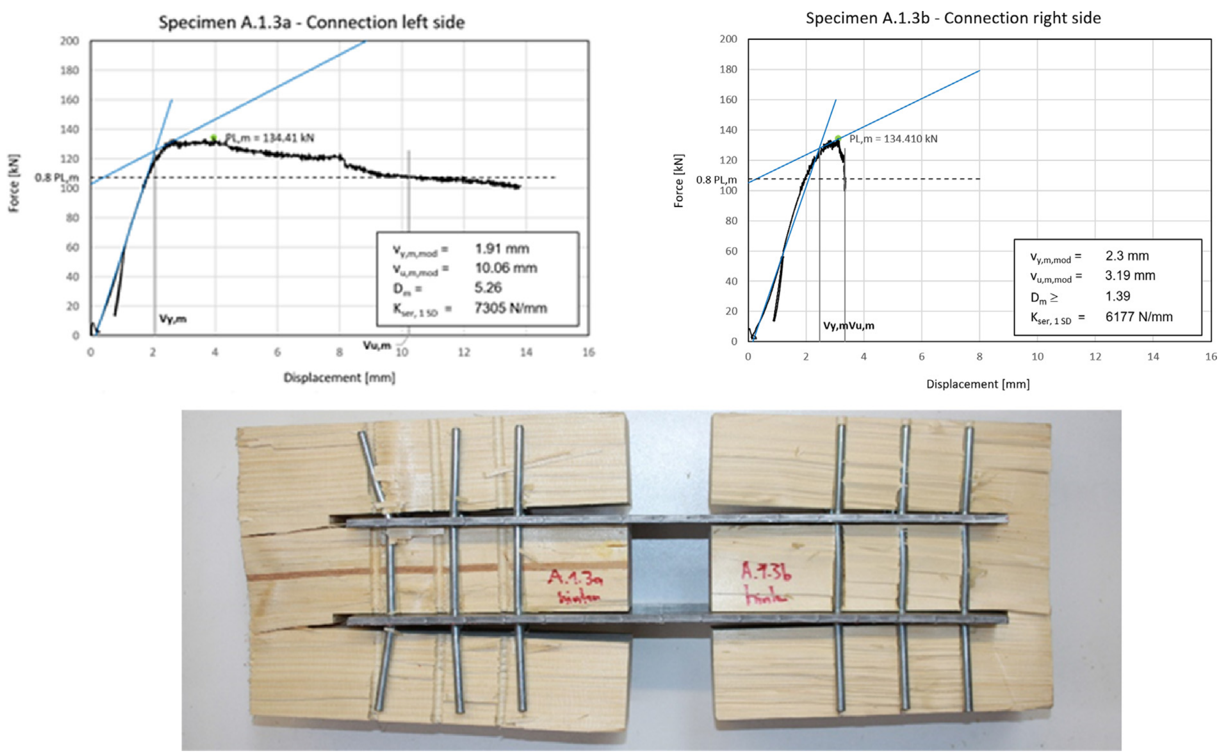

Fig. 1. Force-displacement diagrams and corresponding photograph of two serially arranged doweled assemblies of a connection subjected to shear load in a tensile test. The left side yields until failure while the right side exhibits very low plastic deformation.

modes of these joints were all ductile with plastic hinges developed in all the steel dowels and could be well predicted with the European Yielding Model. In [17] a 3D material model was purposely developed in order to reproduce the test results of hardwood timber joints made using dowels with different steel grades and demonstrating their feasibility, demonstrating that the combination of high-density timber with very high strength steel dowels gives good performance levels. Finally, in [18] dowelled connections in cross-laminated timber made of mild steel and an internal steel plate were tested under monotonic and cyclic loading in order to evaluate theoretically determined overstrength values and study the influence of cyclic loading on overstrength. It was found that cyclic loading does not significantly influence overstrength for connections that respond in a mixed-mode ductile way.

Also regarding ductility, which according to a recent proposal of revision of the timber chapter of Eurocode 8 [19] can be defined as the "*ratio between the ultimate deformation and the deformation at the end of elastic behaviour*" a wide variety of values can be found in literature. While the definition of ductility may seem straightforward, there is not yet an international agreement on the definition of an appropriate cycling testing procedure and yield point. In [20] six different methods used in the calculations of the yield point and ductility ratio are compared in various types of connections and wall assemblies, demonstrating that differences up to 100% can be found in the calculations of the ductility ratio. In fact, while there is a common agreement about the definition of the ultimate displacement (defined as the displacement corresponding to 80% of the maximum load in the descending portion of the 1st cycle backbone curve in a cyclic test), for the evaluation of the yield displacement of mechanical joints in timber structures and the loading protocol for cyclic testing different methods, sometimes quite different one from each other, are proposed in literature as observed in [21]. With this regard, an interesting proposal to determine the low-cyclic fatigue strength of different typologies of dissipative timber connections based on interaction between the strength degradation and the ductility capacity is presented in [3].

However, all the studies conducted so far did not focus on the post-elastic properties of steel, which greatly influence the ductile behaviour of such joints and consequently the provisions included in timber design codes does not consider such properties. According to Eurocode 8 [1], in order to ensure that the given values of the behaviour factor may be used for the different structural types, the ductility properties of the dissipative zones should be demonstrated by means of two alternative possibilities: either by demonstrating through testing performed according to EN12512 [22] that (i) "*the dissipative zones shall be able to deform plastically for at least three fully reversed cycles at a static ductility ratio of 4 for ductility class M structures and at a static ductility ratio of 6 for ductility class H structures, without more than a 20% reduction of their resistance*" or (ii) by applying alternative prescriptive rules. These latter ones state that the above given provisions may be regarded as satisfied in the dissipative zones of all structural types classified in ductility class H if the following conditions are met:

a) in doweled, bolted and nailed timber-to-timber and steel-to-timber joints, the minimum thickness of the timber connected members is 10d and the fastener-diameter d does not exceed 12 mm;
b) in shear walls and diaphragms of Light-Frame construction, the sheathing material is wood-based with a minimum thickness of 4d, where the nail diameter d does not exceed 3,1 mm.

If the above requirements are not met, but the minimum member thickness of 8d and 3d for case a) and case b), respectively, is assured, the dissipative zones of all structural types can be regarded as ductility class M.

These provisions were slightly modified in the above-mentioned proposal of revision of the timber chapter of Eurocode

8 [19] which was partly anticipated in [23], by proposing a third "performance-based" alternative, which require the attainment of a certain ductile failure mode in the dissipative joint according to the European Yielding Model (or Johansen equations) as given in Eurocode 5 [4]. The calculation of the joint strength according to the European Yielding Model is in turn depending on the calculation of the embedment strength of the timber or wood-based member and on the calculation of the yield moment, which is in turn depending on the fastener diameter and on the characteristic tensile strength of steel. Also the prescriptive requirements described above were implemented by requiring that the characteristic ultimate tensile strength of the metal fastener $f_{u,k}$ should be not greater than 450 MPa for bolts and dowels in DC2 (former Ductility Class Medium) and DC3 (former Ductility Class High), 800 MPa for nails and screws in DC2 and DC3, 1000 MPa for staples in DC2.

However, for reinforced concrete ductile walls, post-elastic characteristics are required for the reinforcing steel bars [10]. In different design codes, e.g. [24] or [25], minimal values of hardening ratio $k_s = f_u/f_y$ (with f_y = yield strength) and of elongation at maximum tensile stress A_{gt} are required. Inspired by this fact, the possibility of solving the dysfunction of the serial yielding by using dowels made of steel with high hardening ratio and elongation at maximum tensile stress is examined. This paper investigates the influence of these two post-elastic properties of the steel used for the dowels on the ductility of timber connections.

3. Materials and methods

3.1. Steel properties

3.1.1. Properties of steel currently used for timber structures

As explained in the previous paragraph, in timber engineering and timber design codes, only requirements concerning the ultimate tensile strength f_u are specified. This is a minimal value and may be freely exceeded in accordance with many standards currently in force. However, the relationship between the ultimate tensile strength f_u and the yield strength f_y is generally not defined in timber codes.

A common steel grade used for dowels in Europe is S355. Several timber construction companies use a cold-rolled 11SMnPb37 which is supplied and calculated as S355. This steel has the following mechanical properties: the mean value of the hardening ratio ks amounts to 1.02 and the mean value of the elongation at maximum tensile stress Agt is 3.9%. Other steel qualities supplied as S355 for dowels in Europe exhibit similar values.

3.1.2. Steel properties for ductile structural walls made of reinforced concrete

As for timber construction, the main material used in concrete construction is brittle. The required ductility can only be achieved by means of the reinforcing bars. Therefore, requirements are placed on the mechanical properties of the reinforcing steel. Principle 24 from Bachmann's guidelines [10] states: "*Use ductile reinforcing steel with $R_m/R_e \geq 1.15$ and $A_{gt} \geq 6\%$*". *R_m/R_e corresponds here to the hardening ratio $k_s = f_u/f_y$. If k_s is too small, the plastic deformations concentrate largely on only one single crack ("one-crack hinge"), which leads to an early fracture of the reinforcing bars located at the edge of the wall*". Interestingly in 2003 Bachmann [10] writes: "*Designations such as «reinforcing steel in accordance with [...]» or «fulfils the building code requirements» or «ductile» or «very ductile» etc. are insufficient and misleading because the current building codes are themselves insufficient.*"

3.1.3. Steel for dowels

The purpose of this work is to test whether the use of a steel grade with optimized post-elastic properties makes possible:

- to solve the problem of the dysfunction of the serial yielding and
- to improve the connection ductility.

With these aims, two different qualities of steel for the dowels were examined. The first quality must approximately correspond to what is required for reinforcing bars. The second quality must exhibit higher values because of the wide statistical dispersion of the mechanical wood properties.

The first step was to find steel with the desired properties and in the right format for dowels. Since no steel fulfilling these requirements could be found at that time on the market, two steel types subjected to a recrystallization annealing were finally used. Fig. 2 shows the stress-elongation diagrams of six different steel grades, two of them obtained by annealing.

For both annealed steels, the yield plateau is clearly visible while it is not present for the commonly used cold-rolled steels. Stainless steel theoretically exhibits the required values; however, this steel cannot be used either because no yield plateau is present. Thus, none of the standard steels offers the desired post-elastic properties.

All samples had a diameter of 6 mm and a length of 178 mm. Five specimens per steel grade were tested according to EN10002-1 [26]and using a testing machine Zwick 200 kN. Table 1 shows that the mean values obtained by testing strongly overpass the code requirements (S355 with fu = 650 MPa $\gg$ 490 MPa according to EN10025-2 [27] and nails with fu = 795 MPa and 707 MPa $\gg$ 600 MPa in accordance with EN14592 [28]. This strong exceeding has already been observed for other connectors and seems to be quite frequent and deserves a comment. Indeed, for this product range, the minimum requirements must be met, and no upper limit value is imposed according to the most current codes. With values well above the code requirements, suppliers comply with the standards.

In order to investigate the influence of the strain hardening ratio on the ductility of doweled timber connections, the following three steel qualities have been chosen (Table 2): (1) S355 (11SMnPb37), a steel commonly used for dowels in Europe with k_s = 1.03; (2) annealed ETG100 with k_s > 1,2; and (3) annealed S355 (11SMnPb37) with k_s greater than 1,4. Number of samples, testing standard and statistics are given in table 1.

3.2. Specimens, test and evaluation methods

All specimens were made of Glulam GL24h according to EN 14080:2013 [29] or Laminated Veneer Lumber (LVL-C) made of cross-bonded layers (Kerto-Q from Metsäwood [30]) with a cross section of 100 $\times$ 180 mm^2. Two slotted-in S355 5 mm thick steel plates were inserted and fastened with 9 steel dowels with a diameter of 6.0 mm. Note that according to Eurocode 5 [4], for dowelled connections the dowel diameter should be greater than 6 mm and less than 30 mm, therefore 6 mm dowels are not allowed. However, for the sake of this research it was decided to use 6.0 mm dowels in order to enhance the ductile properties of serially arranged dowelled connections. The timber section was designed with sufficient overstrength ($\gamma_{Rd} \geq 1.6$) in accordance with the recommendation from [23], [21] and [31]. Moreover, different types of confinement were case-by-case implemented in order to ensure that only the steel quality is tested and not the failure of the timber member. For the sake of comparison, specimens without confinement were also tested.

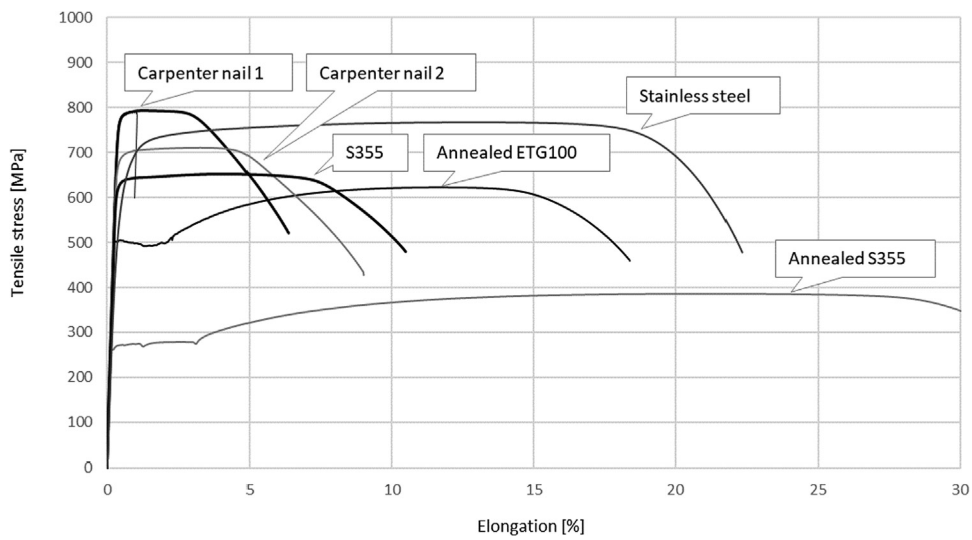

Fig. 2. Stress-elongation diagrams of six different steels, four of them are standard steels found on the market, the other two are obtained by annealing.

Table 1
Mean values of strain hardening ratio k_s, elongation at maximum tensile stress A_{gt}, yield strength f_y and ultimate tensile stress f_u of six different steel types.

Steel designation	ks [−]	Agt [%]	fy [MPa]	fu [MPa]
Carpenter nail 1	1.01	1.0	789	795
COV [%]	*31.8*	*0.2*	*1.3*	*1.4*
Carpenter nail 2	1.04	3.4	682	707
COV [%]	*5.2*	*0.6*	*1.3*	*0.8*
S355 (11SMnPb37)	1.03	4.2	630	650
COV [%]	*4.7*	*0.1*	*0.4*	*0.2*
Stainless steel	1.26	11.8	614	772
COV [%]	*6.1*	*0.9*	*0.9*	*0.4*
Annealed ETG100	1.23	12.2	512	627
COV [%]	*4.5*	*1.2*	*3.2*	*2.0*
Annealed S355 (11SMnPb37)	1.46	20.7	265	386
COV [%]	*1.5*	*2.3*	*2.0*	*0.6*

Table 2
Mean values of strain hardening ratio k_s, elongation at maximum tensile stress A_{gt}, yield strength f_y and ultimate tensile stress f_u of the selected steel types.

Steel designation	k_s [−]	A_{gt} [%]	f_y [MPa]	f_u [MPa]
S355 (11SMnPb37)	1.03	4.2	630	650
Annealed ETG100	1.23	12.2	512	627
Annealed S355 (11SMnPb37)	1.46	20.7	265	386

3.2.1. Monotonic tension tests

Four different specimens were subjected to monotonic tension tests. In the first three specimens (Alpha 1) only the steel grade of the dowels was varied. These first three types were unconfined. For the fourth type (Alpha 2), the steel of the specimen Alpha 1 with the best results was chosen. Furthermore, the specimens Alpha 2 was confined using fully threaded screws. Figs. 3 and 4 show the general layout of these specimens.

The timber members were assigned to each series, so that each of the Alpha 1 type had approximately the same average density and the same dispersion. Detailed characteristics of specimens Alpha 1 and Alpha 2 are given in Table 3. Tests were performed in triplicates.

Tests were carried out according to EN 26891:1991 [32]. A horizontal machine "GEZU" for tensile strength testing with a maximal capacity of 850 kN was used. "TextXpert II from Zwick GmbH was used as testing software. Based on previous tests on similar timber connections, the ultimate tensile force was estimated at about 140 kN. The monotonic tension tests were also performed to provide the yield displacement V_y that is required to carry out the planned cyclic tests. V_y was determined according to EN12512 [22]. However, as the connections have different initial slip, this slip is subtracted from the yield displacement $V_{y,m}$ and from the ultimate displacement $V_{u,m}$ (index "m" for monotonic to distinguish it from the cyclic test results marked with the index "c"). The ductility from the monotonic tests was determined as follows:

$$D_m = \frac{V_{u,m,mod}}{V_{y,m,mod}} \tag{1}$$

In order to quantify the serial yielding, two different approaches were considered. A first reference value was obtained by adding the ultimate displacements of both symmetrical left and right assemblies of dowels and dividing them by the sum of their yield displacements. This value is named $D_{a+b,m}$ and it describes the ductility of two serially arranged connections.

$$D_{a+b,m} = \frac{V_{u,m,mod,a} + V_{u,m,mod,b}}{V_{y,m,mod,a} + V_{y,m,mod,b}} \tag{2}$$

If both assemblies yield similarly, this results in a higher member ductility in comparison with a connection in which mainly one of the two assemblies yields.

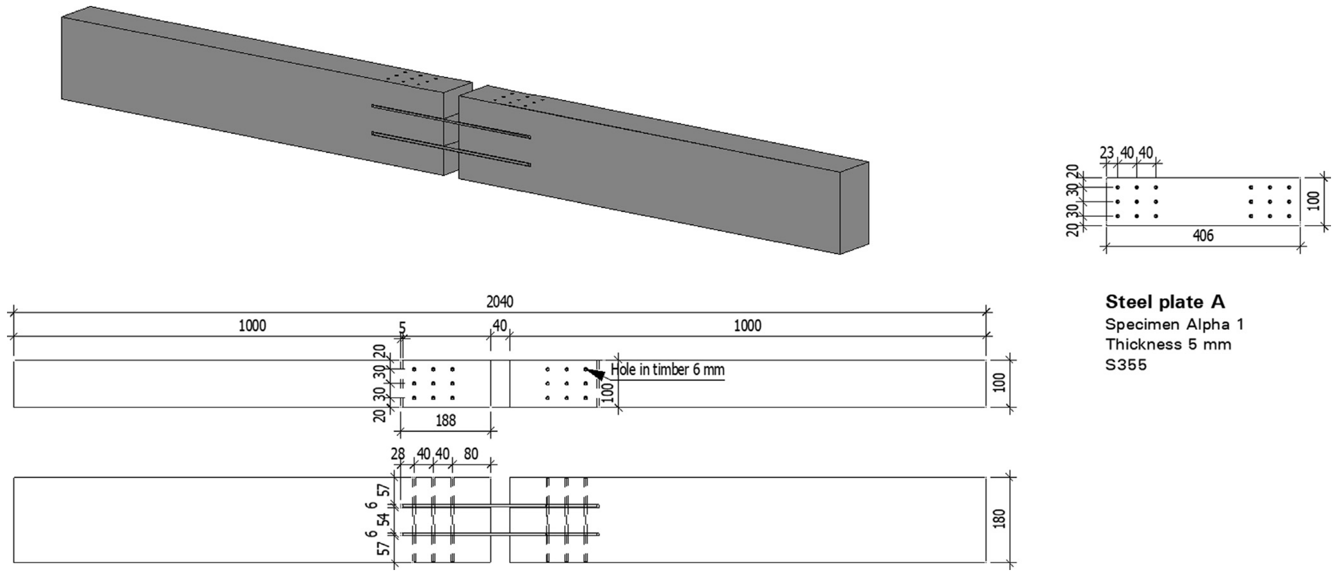

Fig. 3. Layout of specimens Alpha 1, ID A.1, A.2, A.3 (Glulam GL24h without confinement).

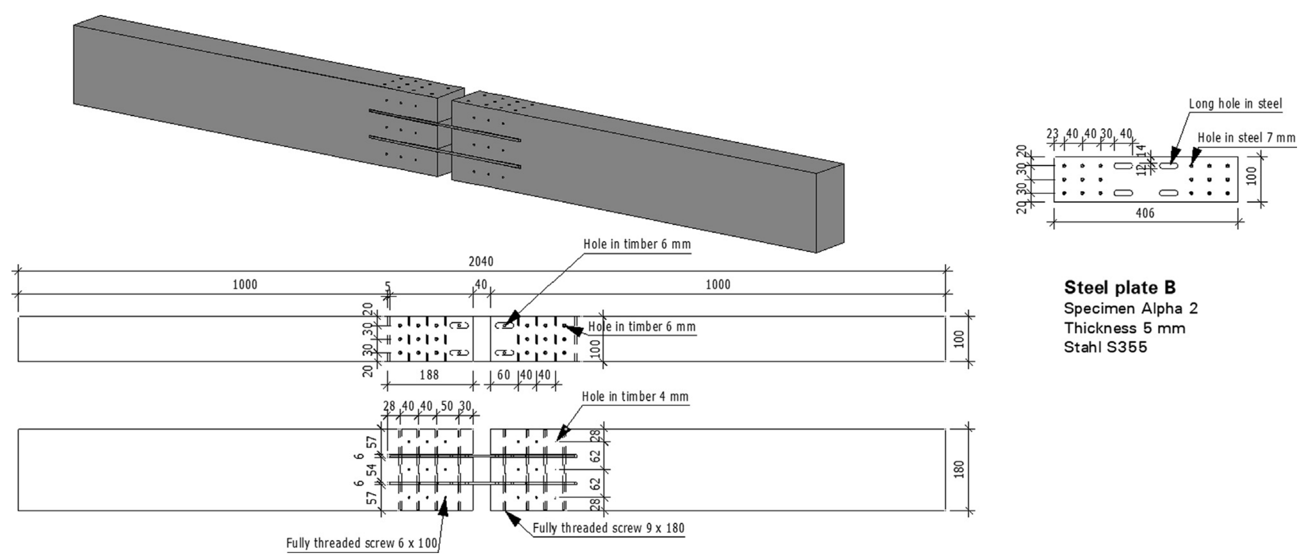

Fig. 4. Layout of specimen Alpha 2, ID A.4 (GL24h with confinement made with fully threaded screws).

Table 3
Designation and details of the 12 specimens (triplicates) of the monotonic tension test.

Specimen Type	Specimen ID	Timber density at 12% moisture content [kg/m^3]	Moisture content [%]	Dowels steel type	k_s [–]
Alpha 1 (without confinement)	A.1	428	11.8	S355 (11SMnPb37)	1.03
	A.2	423	11.7	Annealed ETG100	1.23
	A.3	431	11.5	Annealed S355 (11SMnPb37)	1.46
Alpha 2 (with confinement)	A.4	452	11.9	determined on the basis of the results obtained for A.1 to A.3 (Annealed ETG100)	

A second reference value is obtained by setting the ultimate displacement of the connection that yielded the least in relation with the ultimate displacement of the connection that yielded the most. This value is named Ultimate Displacement Ratio (UDR):

$$UDR = \frac{V_{u,m,mod,min}}{V_{u,m,mod,max}} \tag{3}$$

3.2.2. Cyclic tests

3.2.2.1. Specimens. For the cyclic tests conventional GL24h was used with all steel grades as reference (Beta 1). Since this material is relatively inhomogeneous and early splitting cannot be excluded, Laminated Veneer Lumber (LVL-C) made of cross-bonded layers (Kerto-Q from Metsäwood) was also used as an additional configuration (Beta 2). Transversal splitting was avoided by using LVL members, while perpendicular splitting was avoided using two fully threaded screws. Slotted holes were arranged in the slotted-in steel plates so that the screws were loaded in the axial direction only.

The test specimens consisted of one wood-based member with different connections at each end: one to fix the sample to the testing machine, and the other one to be cyclically tested (Figs. 5 and 6). The test connection was made up of 3 × 3 dowels with a diameter of 6.0 mm (similar to the monotonic test). With the smallest member thickness of t_2 = 54 mm = 9d ≥ 8d, this assembly can be regarded as ductility class M according to Eurocode 8 [1]. According to the calculation based on the Johansen equations of Eurocode 5 [4], the connection layout fulfils the requirements for plastic behaviour, reaching a mode "g" failure for double shear steel-to-timber connections. Moreover, inspired by the Swiss code for timber structures SIA 265 [33] the spacing in the force direction was increased by a factor of 1.5 to avoid an early splitting of the glulam members under cyclic loading. The fixing connection includes 3 × 5 dowels made of commonly used steel and a diameter of 6.3 mm. Thus, both the load carrying capacity and the stiffness of the fixing connection were significantly higher. This made it possible to guide the displacement-controlled test *via* the test connection.

The timber members were assigned to each series, so that each of them had approximately the same average density and the same dispersion. Table 4 gives the details about the specimens Beta 1 and Beta 2.

3.2.2.2. Test method. The tests were carried out according to EN 12512 [22] using a home-made testing frame controlled by the testing software DION 7 from Walter + Bai. The testing frame has a maximal capacity of 1000 kN both in tension and compression. The test was displacement controlled according to EN 12512 [22]. The initial value was the yield displacement $V_{y,m}$ determined on the basis of the monotonic test series. $V_{y,m}$ values ranged between 2.2 mm and 2.6 mm. In order to obtain comparable results, the cyclic tests were conducted for all specimens using an average value of $V_{y,m}$ = 2.4 mm.

3.2.2.3. Evaluation. As a first step, the evaluation was carried out strictly according to the current version of EN12512 [22]. However, as this test standard and Eurocode 8 are currently under revision, in a second stage the evaluation was done according to the proposal of revisions of both standards referenced in [19], [23] and [34].

In order to get results according to the standard *currently* in force, the test method used was that of the current standard. After the tests, the evaluation method described in the revision of EN 12,512 was used. The reason behind this choice was to obtain a better comparison of the series. The revision proposal gives a way to get ductility values with decimals, which is not possible according to the current version which merely indicates whether a ductility of 1, 2, 4 etc. is reached or not.

In the proposal for the revision of EN 12512 [34] the ultimate displacement of the cyclic test, $V_{u,c}$ is defined as the minimum value between the displacements in a cyclic curve corresponding to:

a) failure.
b) the displacement related to 80% of the peak load $P_{L,c}$ evaluated on the first load envelope curve after the peak load.
c) the displacement characterized by a strength degradation factor $k_{deg}(v)$ equal to or lower than $k_{deg,min}$, whichever occurs first. The value of non-dimensional coefficient $k_{deg,min}$ is set on 0.75 in accordance with the current draft to Eurocode 8 [19].

The ductility obtained through the cyclic test is defined as follows:

$$D_c = \frac{V_{u,c}}{V_{y,c}} \tag{4}$$

Fig. 7 shows the evaluation of the cyclic ductility D_c. In this case, the ultimate displacement $V_{u,c}$ was capped by the strength degradation criteria $k_{deg,min}$.

3.2.3. Study of serial yielding

3.2.3.1. Specimens. In order to test the influence of the steel quality, early brittle failures of the timber members due to cracking or splitting should be prevented. For this reason, only LVL-C members were used. The test specimens consisted of a single member with two identical assemblies of dowels at each end. The end connections were made up of 3 × 3 dowels and are identical to the ones used in the monotonic and cyclic tests (Fig. 6, steel plate E). The timber members were assigned to each series, so that each of them had approximately the same average density and the same dispersion. Table 5 summarises the characteristics of Gamma 1 and

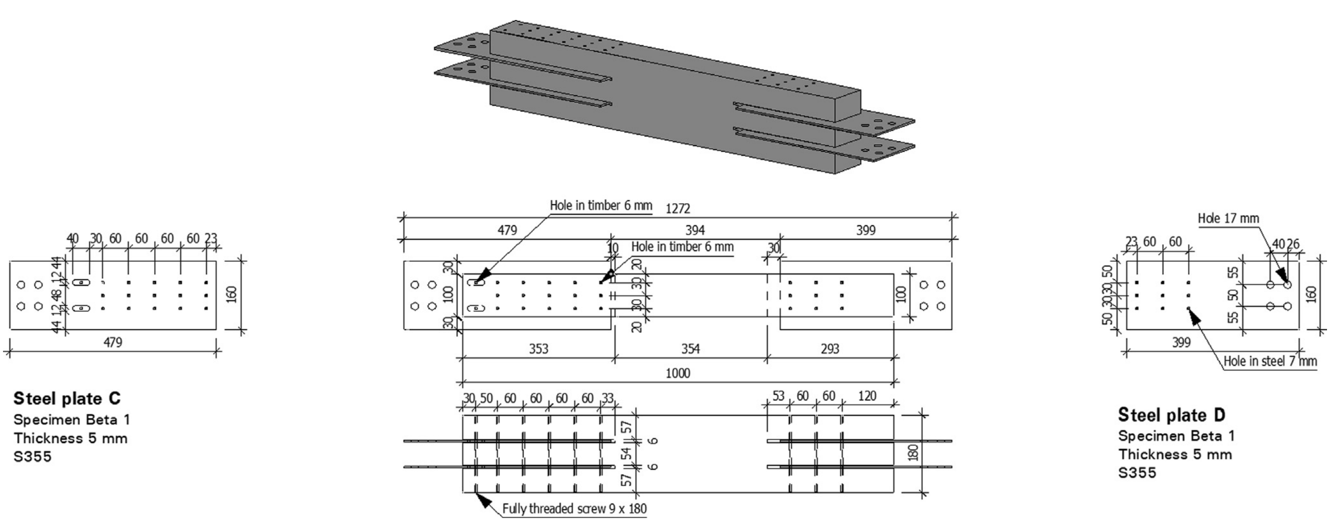

Fig. 5. Layout of specimens Beta 1, specimens ID: B.1, B.2, B.3 (Glulam GL24h without confinement, fixing connection on the left, tested connection on the right).

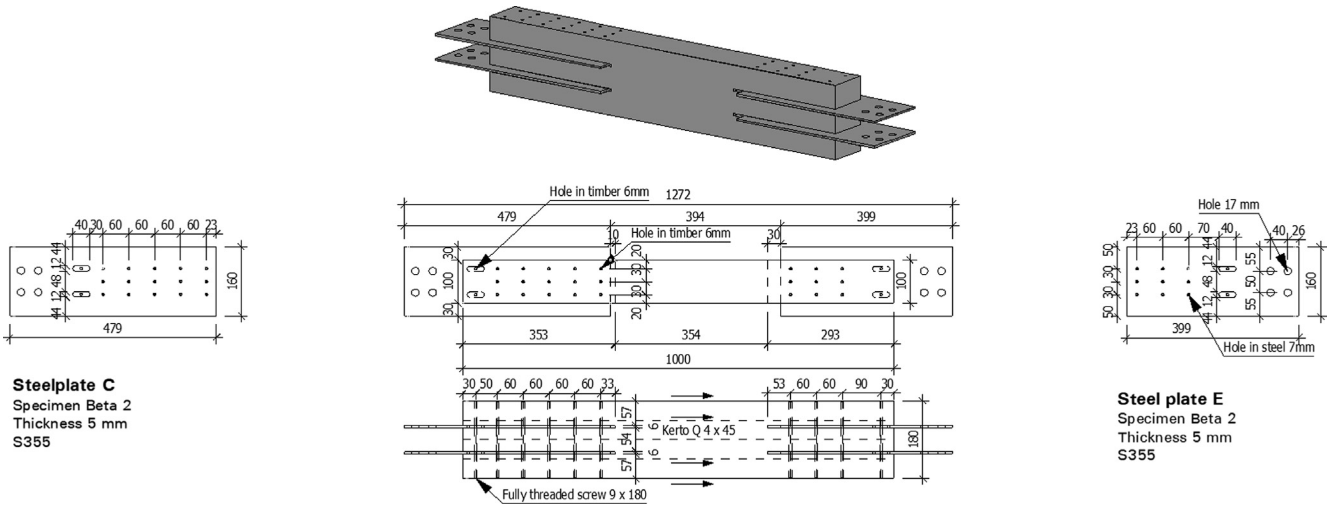

Fig. 6. Layout of specimens Beta 2, specimens ID: B.4, B.5, B.6 (LVL with confinement using fully threaded screws, fixing connection left, tested connection right).

Table 4
Designation and details of the 18 specimens (triplicates) of the cyclic test.

Specimen Type	Specimen ID	Average Timber density at 12% moisture content/LVL density [kg/m^3]	Average Moisture content [%]	Dowel steel	k_s [–]
Beta 1 (Glulam without confinement)	B.1	460	7.9	S355 (11SMnPb37)	1.03
	B.2	462	7.9	Annealed ETG100	1.23
	B.3	465	8.0	Annealed S355 (11SMnPb37)	1.46
Beta 2 (LVL with confinement)	B.4	477	–	S355 (11SMnPb37)	1.03
	B.5	473	–	Annealed ETG100	1.23
	B.6	480	–	Annealed S355 11SMnPb37	1.46

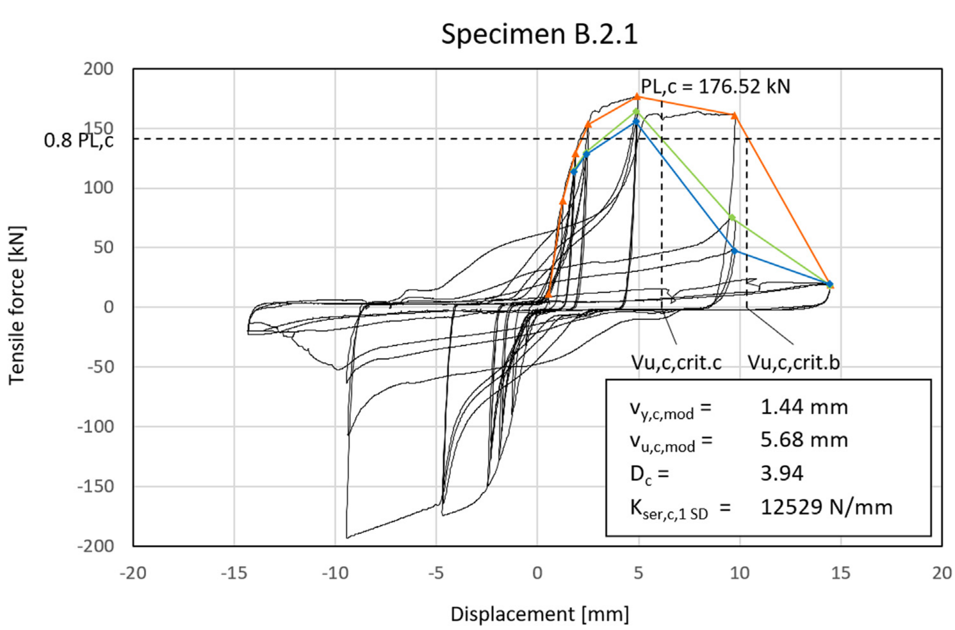

Fig. 7. Example of the evaluation from a connection under cyclic loading according to the proposal 2020 for revision of the EN 12512 [34] (specimen B.2.1).

Gamma 2 specimens. For this test series, standard steel was not used because such tests have already been reported [35].

3.2.3.2. Test method. Since there is no standardized procedure for checking the activation of serially arranged connections, a procedure inspired by EN 12512 [22] was chosen using a home-made testing frame controlled by the testing software DION 7 from Walter + Bai. However, the displacement was not controlled *via* a connection, but *via* the displacement of the testing machine, because it was not possible to know in advance to what extend each connection deforms plastically. To this aim, additional transducers were used to correctly measure the displacements of each connection (note: connection = group of dowels used to fix timber to steel via shear) and the testing machine followed the given displacements and the corresponding displacements of each "connection" were recorded. The theoretical yield displacement of the whole timber member is determined assuming a uniform behaviour of both connections until the previously defined yield displacement of 2.4 mm. The displacement of the testing machine amounts to two times 2.4 mm plus a compensation for its own elastic deformation. Based on the evaluation of the cyclic tests, this compensation was estimated at 2.0 mm. Thus, a value of 6.8 mm was chosen as V_y for the control of the testing machine.

3.2.3.3. Evaluation. As for the test method, no standardized evaluation method is available concerning serial yielding. At first, the behaviour of both connections of the member was plotted in the same diagram. A typical example of such diagram is shown in Fig. 8.

Both curves largely overlap up to a certain point, from which they diverge strongly. This point can be found by calculating the displacement difference of both curves at each displacement and recording it over time, as shown in Fig. 9.

This point of beginning divergence of the connection displacements is determined in such a way that it marks the moment when the displacement difference begins to exceed the previously usual values, in particular the displacement difference of the cycle completed immediately before the beginning of the divergence. In order to give a quantitative assessment of the serial yielding, the mean value of the connection displacements at the point of beginning divergence between both connection displacements was calculated.

4. Results and discussion

4.1. Comparison in terms of ductility

4.1.1. Monotonic tests

Table 6 gives the results of the monotonic tension tests. Some results are crossed out because they are influenced to a large extend by wood splitting or cracking despite of an important oversizing of the timber member.

The results given in Table 6 above show a positive influence of the hardening ratio and the elongation at maximum tensile stress on the ductility of timber connections. Furthermore, the difference between the ductility of a single connection and of two serially arranged connections is smaller when dowels made of steel with optimized post-elastic behaviour are used. Due to the very small number of specimens, it is not possible to say whether these effects are significant or not. However, the trend is clear.

Interestingly, this test series shows that the post-elastic properties of the steel used for the dowels are reflected by the behaviour of the connections (Fig. 10). In comparison with connections with dowels made of common steel, the displacement at maximal strength is about 5 times higher for the connections where special dowels are implemented.

The relationship between connection hardening and serial yielding will be further discussed in part 4.2.2.

4.1.2. Cyclic tests

Table 7 gives the results of the cyclic tests. Only the connections with dowels made from annealed ETG 100 (k_s = 1,23) fulfil the requirements for $2xV_y$ which are largely obtained. None of the connections reaches a ductility of 4.

An effective confinement of the timber member is an essential condition in order to benefit from the positive influence of dowels made of steel with improved post-elastic properties. Thus, the crucial importance of preventing early brittle failures in the wooden parts, not only in terms of dimensioning but also regarding the assembly shaping (confinement), is confirmed.

While no dowel failed during the monotonic test, they always broke during the cyclic test as a result of low-cycle fatigue (Fig. 11). Moreover, this failure mechanism of the dowels was probably favoured by holes with sharp edges. As it is generally the case for this type of timber connection, no round or chamfer reducing the notch effect was done.

Surprisingly, the connections with dowels made of steel with the highest hardening ratio and the highest elongation at maximal tensile strength have not led to a higher ductility. An unfavourable hierarchy of the strength (f_y and f_u) of the dowels steel related to the inserted steel plates made of S355 is a possible explanation of this fact. With a yield strength of f_y = 277 N/mm^2 and an ultimate tensile strength of f_u = 418 N/mm^2, it can be expected that the notch starts in the dowels instead of starting in the plate.

Considering that the Beta-type specimens were not suitable for an evaluation of the ductility of serially arranged connections, an estimation was possible based on the results obtained with the Gamma-type test specimens. The mean value of the connection displacement at the point of beginning divergence between both connection displacements was calculated at 7.0 mm for the annealed ETG100 and 7.1 mm for the annealed 11SMnPb37. More details of these results are given in Section 4.2.2. Based on the yield displacement of 1.8 mm obtained from the test series B.5 and B.6, the ductility measured through cyclic tests of two serially arranged connections was estimated at 3.8 for connections with dowels made of steel with favourable post-elastic properties. During similar tests which were done a year before [35], a mean value of the connection displacement at the point of beginning divergence of 3.2 mm was obtained by using dowels made of common steel. Based on a reference yield displacement of 1.5 mm, the ductility measured through cyclic tests of two serially arranged connections was estimated as 2.1 for connections with standard dowels. These series being not identical, the values obtained are not fully comparable. However, the use of dowels made of steel with favourable post-elastic properties substantially increases the connection ductility.

4.2. Serial yielding

4.2.1. Monotonic tests

Table 8 gives the ultimate displacements ratio (UDR) measured as defined in Eq. (3). The results show that the serial yielding is clearly improved thanks to the use of optimized dowels (A.1 com-

Table 5
Designation and details of the 6 specimens (triplicates) of the tests about serial yielding.

Specimen type	Specimen ID	Average LVL density [kg/m^3]	Dowels steel	k_s [–]
Gamma (LVL with confinement)	C1	468	Annealed ETG100	1.23
	C2	465	Annealed S355 (11SMnPb37)	1.46

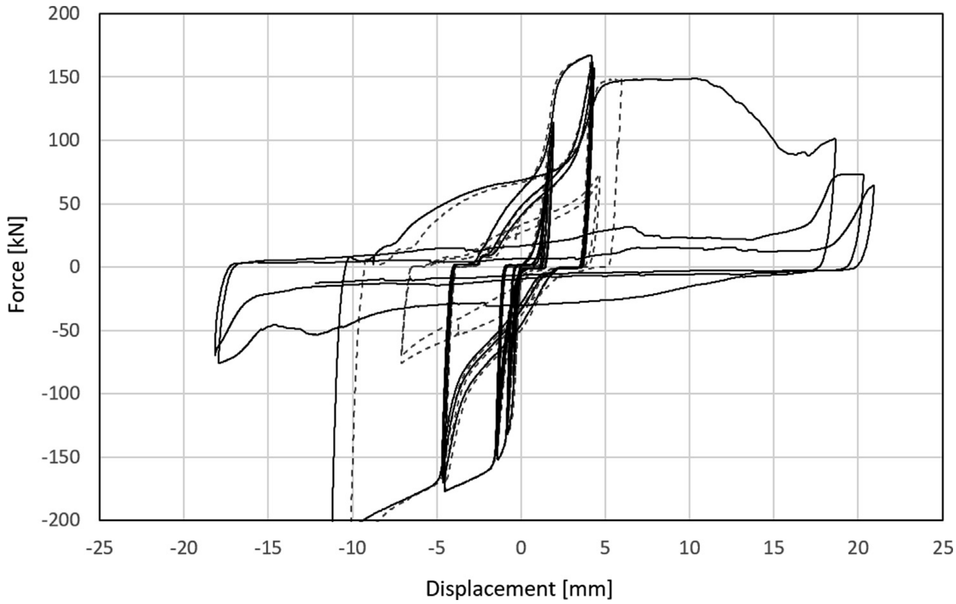

Fig. 8. Example of the force–displacement-curves of the two identical connections of the timber member plotted together in one diagram (specimen C.1.1).

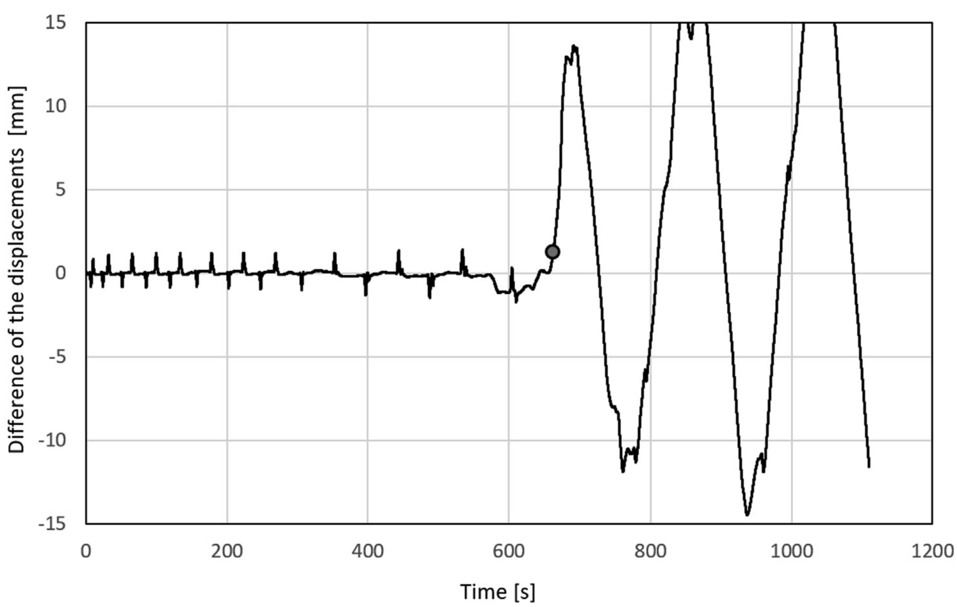

Fig. 9. Difference of the displacements of both connections over time. The displacement difference at the beginning of the divergence of the connection displacements is marked by a dot (specimen C.1.1).

pared to A.2, A.3, A.4). To assess the benefits for the member ductility, the ratio of the ultimate displacements is multiplied by the corresponding connection ductility ($UDR{\cdot}D_m$). Thus, an improvement of about factor 2 appears when using optimized dowels (samples A.1 compared to A.2, A.3, A.4).

Fig. 12 shows a large yielding difference between the single connection D_m and the serial activation (UDR).

4.2.2. Cyclic tests

Table 9 gives the mean value of the connection displacement at the point of beginning divergence between both connection displacements. This value indicates that up to this point both serially arranged connections yielded together.

Based on the yield displacement of 1.8 mm obtained from the test series B.5 and B.6, the ductility measured through cyclic tests of two serially arranged connections was estimated as 3.9 for connections with dowels made of steel with favourable post-elastic properties. In accordance with [35], a mean value of the connection displacement at the point of beginning divergence of 3.2 mm was obtained using dowels made of common steel. Based on the corresponding yield displacement of 1.5 mm, the ductility measured through cyclic tests of two serially arranged connections was estimated as 2.1 for connections with standard dowels. These series being not identical, the values obtained are not fully comparable. However, based on the results of the monotonic tension tests presented in Table 8, an increase factor 2 of the ductility of two serially arranged connections is realistic. In the absence of connection hardening, the connection that starts to yield generally continues until failure, without the other connection being plasti-

Table 6
Comparison in terms of ductility between only one and both serially arranged assemblies of dowels (determined according Eq. (4)) based on the monotonic tension test of 12 specimens.

Specimen ID	Dowels steel with		Connection ductility D_m	Ductility of two serially arranged connections $D_{a+b,m}$	Ratio $D_m/D_{a+b,m}$
	k_s [–]	A_{gt} [%]	[–]	[–]	[–]
A.1.1	1.03	4.2	3.2	2.8	0.88
A.1.2			~~1.9~~	~~1.8~~	–
A.1.3			5.3	3.2	0.60
Average A.1			**4.3**	**3.0**	**0.70**
A.2.1	1.23	12.2	7.6	6.3	0.83
A.2.2			4.7	4.0	0.85
A.2.3			~~3.0~~	~~2.9~~	–
Average A.2			**6.1**	**5.1**	**0.84**
A.3.1	1.46	20.7	4.9	4.7	0.96
A.3.2			~~4.3~~	~~3.5~~	
A.3.3			5.5	5.1	0.93
Average A.3			**5.2**	**4.9**	**0.94**
A.4.1	1.23	12.2	9.2	7.5	0.82
A.4.2			~~3.1~~	~~2.3~~	–
A.4.3			4.4	4.0	0.91
Average A.4			**6.8**	**5.8**	**0.85**
Average A.2 to A.4	–	–	***6.0***	***5.3***	***0.88***

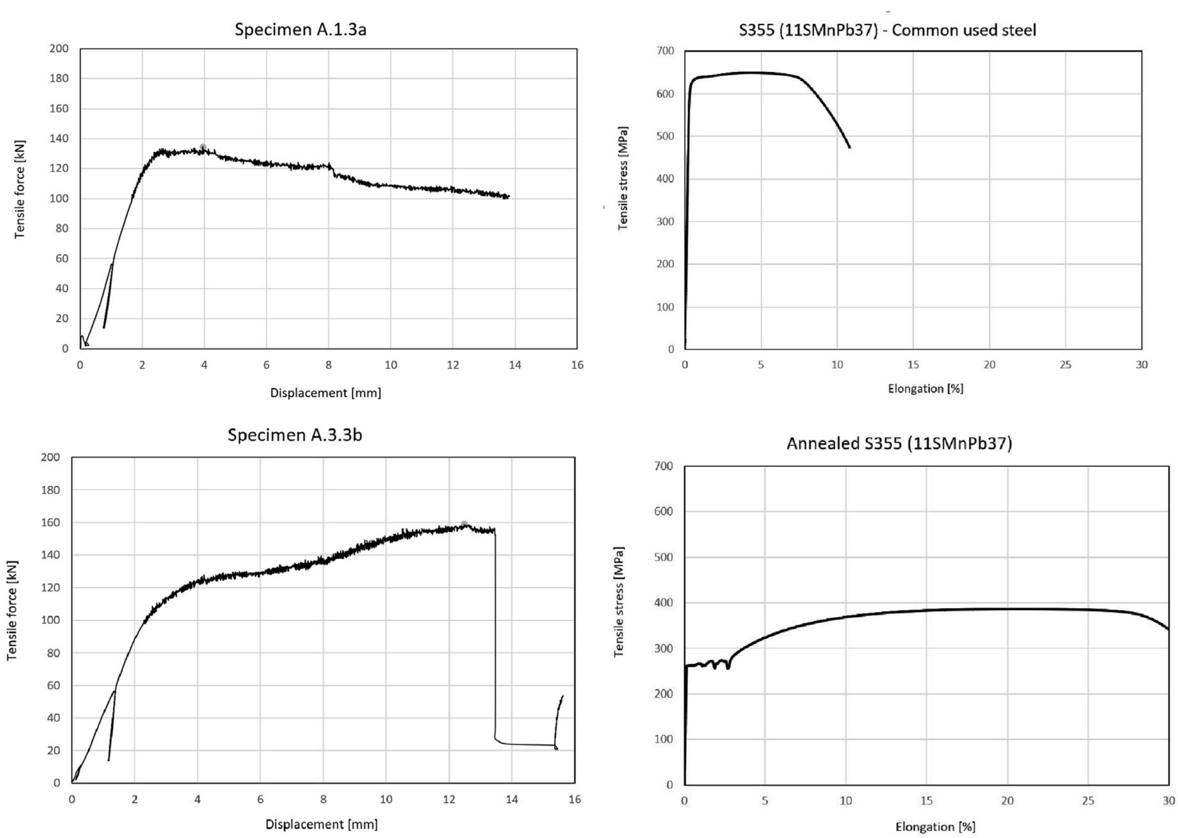

Fig. 10. Examples of force–displacement diagrams of representative specimens of the timber connection (left) and the corresponding stress-elongation diagrams of the steel used for the dowels (right) with commonly used steel (top) and steel with high values of hardening ration an elongation at maximum tensile stress (bottom).

cally solicited to a large extent. Thus, serial yielding requires connection hardening.

The results from monotonic and cyclic tests of the connections with dowels made of the steel with the *highest* post-elastic properties did not show a better serial yielding. This assertion needs to be discussed, especially regarding the cyclic tests. Since no hierarchy was set-up between the strength of the dowels and the strength of the plate, it probably results as an unfavourable notch effect. For this reason, the connections with dowels made of steel with the highest post-elastic properties probably could not develop their full yielding potential. If the fulfilment of a hierarchy of the strengths between dowel and plate as well as round or chamfer of the plate holes make it possible to obtain an almost complete serial yielding remains a question pending. This should be investigated e.g. by applying requirements as the following:

$$\text{Hierarchy of the strengths}: f_{u,plate} \leqslant 0.8\ f_{y,dowel} \quad (5)$$

Table 7
Ductility of the 18 specimens (triplicates) of the cyclic test evaluated according to the current EN 12512 [22] and to the revision proposal 2020 [34].

Specimen Type	Specimen ID	k_s	Number of specimens that have fulfilled the requirements of EN12512 out of the 3 tested specimens			Mean connection ductility according to the revision proposal 2018
		[–]	V_y	2 V_y	4 V_y	D_c
Beta 1 (Glulam without confinement)	B.1	1.03	1	1	0	2.8
	B.2	1.23	1	3	0	3.1
	B.3	1.46	3	0	0	2.2
Beta 2 (LVL with confinement)	B.4	1.03	3	1	0	2.8
	B.5	1.23	3	3	0	3.6
	B.6	1.46	3	1	0	3.7

Fig. 11. Cyclic tested and opened connection with broken dowels due to low-cycle fatigue (specimen B.3.2).

$$\text{Round of the steel plate holes}: r_{min} \geqslant 0.2\ d \qquad (6)$$

Being difficult to open the LVL-C specimens of this gamma-series, in order to photograph their plastically deformed dowels, the connections were x-rayed (Fig. 13).

4.3. Resistance and stiffness

The tests also showed interesting results concerning resistance and stiffness. Table 10 gives ultimate resistance and slip modulus obtained from both the monotonic tension test and the cyclic test. Some results are crossed out because they are influenced to a large extend by wood splitting or cracking.

The results are surprising at a first sight: the connections with dowels made of the steel with the lowest strength obtain sometimes higher values than some connections with dowels made of a steel with about twice as high strength values. In the monotonic test of non-confined specimens, the specimens A.3 (with the lowest strength values for the dowels) even reached higher ultimate resistances than the connections with dowels made of commonly used steel. Only in the cyclic tests the specimens with dowels made of steel with lowest strength were less resistant than those for which standard steel was used. A plausible explanation of this fact was already discussed in Section 4.1.2 and could be due to an unfavourable hierarchy of the strength.

At equal steel strength, the connections in which dowels made of steel with optimized post-elastic properties are used are about 1/3 stronger than those comprising dowels made of standard steel. The connections with dowels made of steel with strengths comparable to the commonly used steel but with optimized post-elastic properties give consistently both higher ultimate resistances and higher stiffnesses. Even the lowest ultimate resistance of connections with improved dowels is never exceeded by the most resistant connection made of common dowels. These results are likely to question certain design principles. In accordance with the current dimensioning methods, if the wood thicknesses are sufficient, an increase of the steel strength generally leads to an increase of the design value R_d of the connection. This is not confirmed by the tests conducted here. A possible explanation concerns the group action of the dowels, which is generally taken into account

Table 8
Ultimate displacements ratio and connection ductility of the 12 specimens of the monotonic tension test.

Specimen Type	Specimen ID	Dowels steel		UDR	Connection ductility D_m	UDR·D_m
		k_s [–]	A_{gt} [%]	[–]	[–]	[–]
Alpha 1 (Glulam without confinement)	A.1.1	1.03	4.2	0.68	3.2	2.2
	A.1.2			~~0.81~~	~~1.9~~	–
	A.1.3			0.32	5.3	1.7
	Average A.1			**0.50**	**4.3**	**2.2**
	A.2.1	1.23	12.2	0.81	7.6	6.2
	A.2.2			0.75	4.7	3.5
	A.2.3			~~1.00~~	~~3.0~~	–
	Average A.2			**0.78**	**6.1**	**4.8**
	A.3.1	1.46	20.7	0.90	4.9	4.4
	A.3.2			~~0.79~~	~~4.3~~	–
	A.3.3			0.68	5.5	3.7
	Average A.3			**0.79**	**5.2**	**4.1**
Alpha 2 (Glulam with confinement)	A.4.1	1.23	12.2	0.61	9.2	5.6
	A.4.2			~~0.86~~	~~3.1~~	–
	A.4.3			0.71	4.4	3.1
	Average A.4			**0.66**	**6.8**	**4.5**
	Average A.2 to A.4	–	–	***0.74***	***6.0***	***4.5***

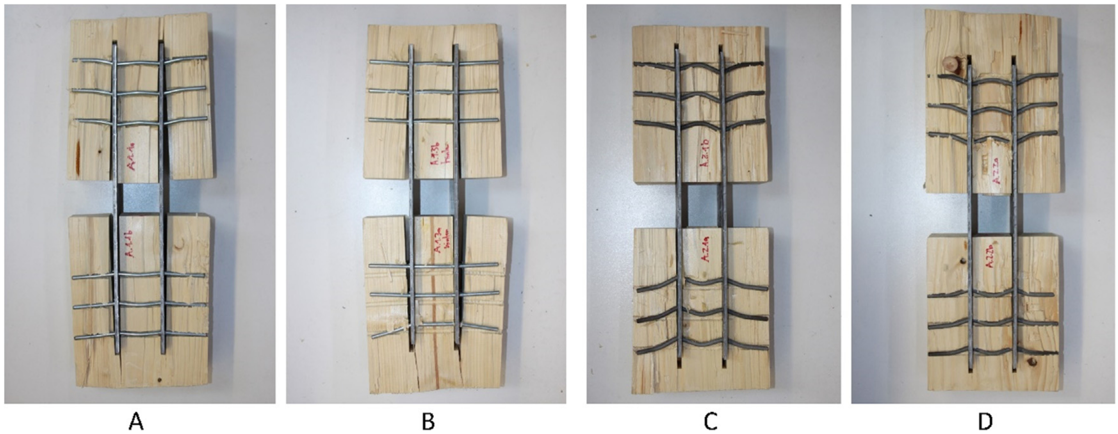

Fig. 12. Photographs of tested and opened connections. Left: dowels made of common steel (specimens A.1.1 (A) and A.1.3 (B)); right: dowels made of steel with optimized properties (specimens A.2.1 (C) and A.2.2 (D)).

Table 9
Mean value of the connection displacement at the point of beginning divergence between both connection displacements of the 6 specimens of the serial yielding tests.

Specimen Type	Specimen ID	Dowels made of steel with		Mean value of the connection displacement at the point of beginning divergence
		k_s [–]	A_{gt} [%]	[mm]
Gamma (LVL with confinement)	C1.1	1.23	12.2	5.8
	C.1.2			8.6
	C.1.3			6.7
	Average C.1			**7.0**
	C.2.1	1.46	20.7	6.2
	C.2.2			5.6
	C.2.3			9.5
	Average C.2			**7.1**
	Average C.1 and C.2	–	–	***7.0***

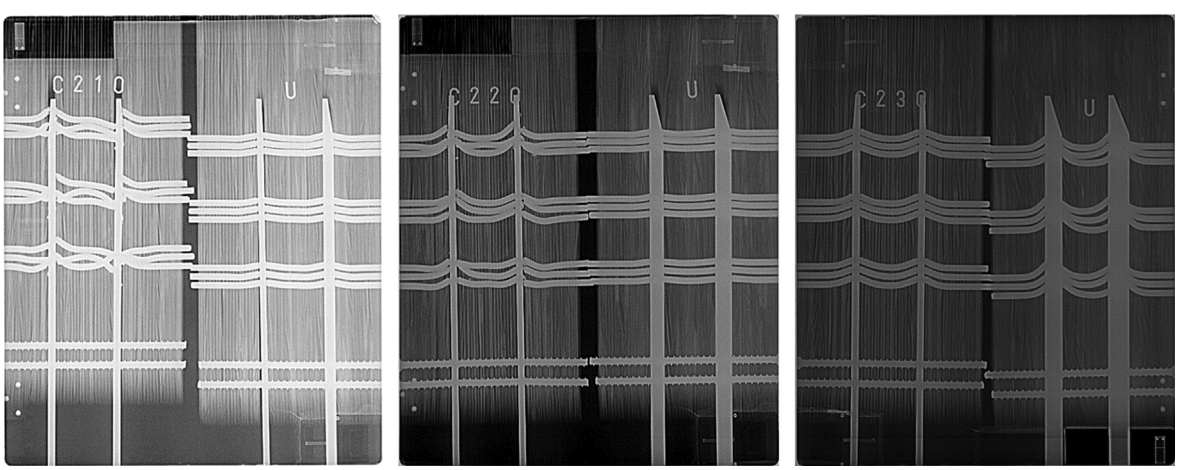

Fig. 13. X-rays of all connections of the C2 test series after testing of serial yielding (left: C2.1, middle: C2.2, right: C2.3).

through the effective number of fasteners n_{ef} of the connection: the resistance reducing influence of dowels made of steel with low strength values could well be compensated, even overcompensated thanks to a better group action, meaning a higher n_{ef} value. It is likely that due to the hardening of the connection and the circa 5 times greater displacement at maximal strength, each dowel may contribute more favourably to the connection resistance. Furthermore, a softer introduction of forces through dowels made of steel with favourable post-elastic properties is expected, which is confirmed by the good results of the unconfined A.3 and B.3 series.

An interesting point is noted concerning stiffness. The heat treatments performed on the steels used for the dowels do not influence their modulus of elasticity which stays around 210 GPa. Thus, all the dowels implemented have the same stiffness. Nevertheless, significant stiffness differences are reported between series. Then, the series using dowels made of the steel with the lowest strength are clearly softer than the others. Thus, the mean value of the slip modulus of the series A3 Kser,m = 4′929 N/mm is about 1/3 lower than the corresponding stiffness of the series A1 and A2 (A1: Kser,m = 7′209 N/mm; A2: Kser.m = 7′388 N/m

Table 10
Ultimate resistance and slip modulus (transformed for one dowel) of all specimens of the monotonic tension tests (12 specimens) and of the cyclic tests (18 specimens).

Without confinement						
Dowel properties	Monotonic tests			Cyclic tests		
	Specimen ID	$P_{L,m}$ [kN]	$K_{ser,m,1\ dowel}$ [N/mm]	Specimen ID	$P_{L,c}$ [kN]	$K_{ser,c,1\ dowel}$ [N/mm]
k_s = 1.03	A.1.1	138.5	7113	B.1.1	138.4	10,262
A_{gt} = 4.18%	A.1.2	~~133.5~~	~~6381~~	B.1.2	~~139.8~~	~~8885~~
f_y = 630 MPa	A.1.3	134.4	7305	B.1.3	145.5	7656
f_u = 650 MPa	**Average A.1**	**136.4**	**7209**	**Average B.1**	**141.9**	**8959**
k_s = 1.23	A.2.1	185.2	8382	B.2.1	176.5	12,529
A_{gt} = 12.2%	A.2.2	183.1	6393	B.2.2	189.7	9244
f_y = 512 MPa	A.2.3	~~179.4~~	~~7038~~	B.2.3	177.3	8374
f_u = 627 MPa	**Average A.2**	**184.1**	**7388**	**Average B.2**	**181.2**	**10,049**
k_s = 1.46	A.3.1	148.0	4767	A.3.1	137.1	6221
A_{gt} = 20.7%	A.3.2	~~143.0~~	~~5638~~	A.3.2	142.4	6922
f_y = 265 MPa	A.3.3	158.6	5091	A.3.3	147.3	8320
f_u = 386 MPa	**Average A.3**	**153.3**	**4929**	**Average B.3**	**142.3**	**7154**
With confinement						
k_s = 1.03	–	–	–	B.4.1	150.3	8502
A_{gt} = 4.18%	–	–	–	B.4.2	156.3	9327
f_y = 630 MPa	–	–	–	B.4.3	163.4	11,688
f_u = 650 MPa	–	–	–	**Average B.4**	**156.7**	**9839**
k_s = 1.23	A.4.1	187.6	9356	B.5.1	180.1	10,051
A_{gt} = 12.2%	A.4.2	~~180.2~~	~~8868~~	B.5.2	178.4	11,063
f_y = 512 MPa	A.4.3	199.9	6613	B.5.3	175.9	10,920
f_u = 627 MPa	**Average A.4**	**193.7**	**7985**	**Average B.5**	**178.1**	**10,678**
k_s = 1.46	–	–	–	B.6.1	138.1	7867
A_{gt} = 20.7%	–	–	–	B.6.2	137.0	8103
f_y = 265 MPa	–	–	–	B.6.3	139.5	8520
f_u = 386 MPa	–	–	–	**Average B.6**	**138.2**	**8163**

m). Based on the cyclic test, the samples of the series B3 Kser,c = 7′154 N/mm are in average about 1/4 softer than those of the series B1 and B2 (B1: Kser,c = 8′959 N/mm; B2: Kser.c = 10′049 N/mm). With confinement and based on a the cyclic test, the stiffness difference seems to decrease slightly since it amouts about 1/5 (B6: Kser,c = 8′163 N/mm compared to B4: Kser.c = 9′839 N/mm and B5: Kser.c = 10′678 N/mm). However, since the connection stiffness is measured in the so-called elastic area, the strength of the steel should in principle not influence the connection stiffness, which is not confirmed here. It seems that due to effects (which are not in the scope of this article) local and early yielding of dowels affect the connection stiffness.

4.4. Possible code implementation

None of the connections reaches a ductility of 4 according to EN12512 [22], despite a dowel dimeter lower than 12 mm and a member thickness greater than the minimum thickness of 8d required according to Eurocode 8 [1].

On this basis, there is good reason to doubt that the thickness of wood of 10d required for class H would really have made it possible to achieve a ductility of 6.

According to the calculation of the characteristic load-carrying capacity of the connection based on the European Yielding Model of Eurocode 5 [4], the connection layout fulfils the alternative requirements for a ductile failure mode of the dissipative connection given in the revision of the timber chapter of Eurocode 8 given in [19] and [23] mentioned in §2. However, even when f_u is not greater than 450 MPa (mean value of f_u of the dowels of the specimens B.3 and B.6 equals 386 MPa) the ductility remains low.

The use of a steel grade with targeted properties markedly improves ductility but it's not by itself a sufficient condition in order to achieve the required values.

The question to be answered concerns the possibility of ensuring the required ductility only by means of prescriptive rules related to the quality of materials, dimensioning and detailing. If this approach should prove to be unsuccessful, only the "performance based" alternative would remain.

5. Conclusions

The monotonic and cyclic tests carried out by implementing dowels made of steel with favourable post-elastic properties show that the yielding of two serially arranged ductile zones is possible. The ductility of two serially arranged connections is roughly twice as high as when common steel is used for the dowels. A value of hardening ratio of 1.23 and an elongation at maximum tensile stress of 12.2% seem to be sufficient to make serial yielding possible, although not fully.

By implementing dowels made of steel with favourable post-elastic properties, the monotonic and cyclic connection ductility increases by about 30%. Possibly, this increase could be even heightened by reducing the notch effect in the dowels.

For steel grades with equal steel strength, connections made with optimized dowels are about 1/3 stronger than those made of common dowels.

Connections assembled with dowels made of steel with strengths comparable to the commonly used steel but with optimized post-elastic properties give both consistent higher values of ultimate strength and stiffness. Moreover, the ductility of two serially arranged connections is doubled and the connection displacement at maximum tensile strength is about 5 times higher with respect to the ones with dowels made of common steel.

With the objective to improve the ductility properties of dissipative zones in the seismic design of timber structures, the results question some dimensioning and detailing principles. The following aspects should be therefore further investigated in order to provide safe code requirements:

a) requirements on the post-elastic properties of the steel used for dowel-type fasteners.

b) the way to consider and weight the following three parameters: yield strength, ultimate tensile strengths and the number of effective fasteners of the connection.
c) the set-up of a hierarchy of the strengths between dowels and steel plate.
d) the detailing (e.g. round or chamfer) of the plate holes.

CRediT authorship contribution statement

M. Geiser: Funding acquisition, Resources, Conceptualization, Supervision, Project administration, Methodology, Validation, Writing - original draft. **M. Bergmann:** Methodology, Formal analysis, Investigation, Software, Validation, Visualization. **M. Follesa:** Visualization, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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